Basics of Mechanical Engineering-1

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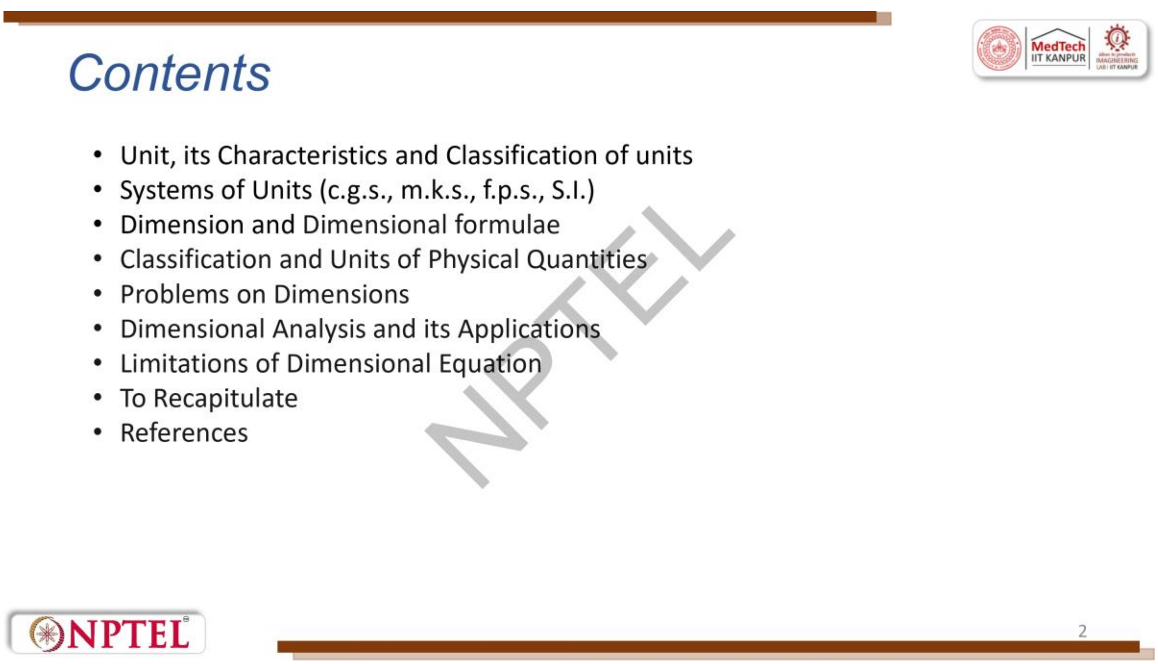
Week 01

Lecture 01

Units, Dimensions and Dimensional Analysis (Part 1 of 2)

Welcome to the lecture series in the course Basics of Mechanical Engineering-I. This course is offered by Professor J. Ramkumar who is a faculty with Department of Mechanical and Design at IIT Kanpur. It is me! Welcome to the first lecture in the course. Here we will be trying to cover the Units and Dimensions, also Dimension Analysis. This is a very very important topic, so we will try to cover that along with Units and Dimensions.

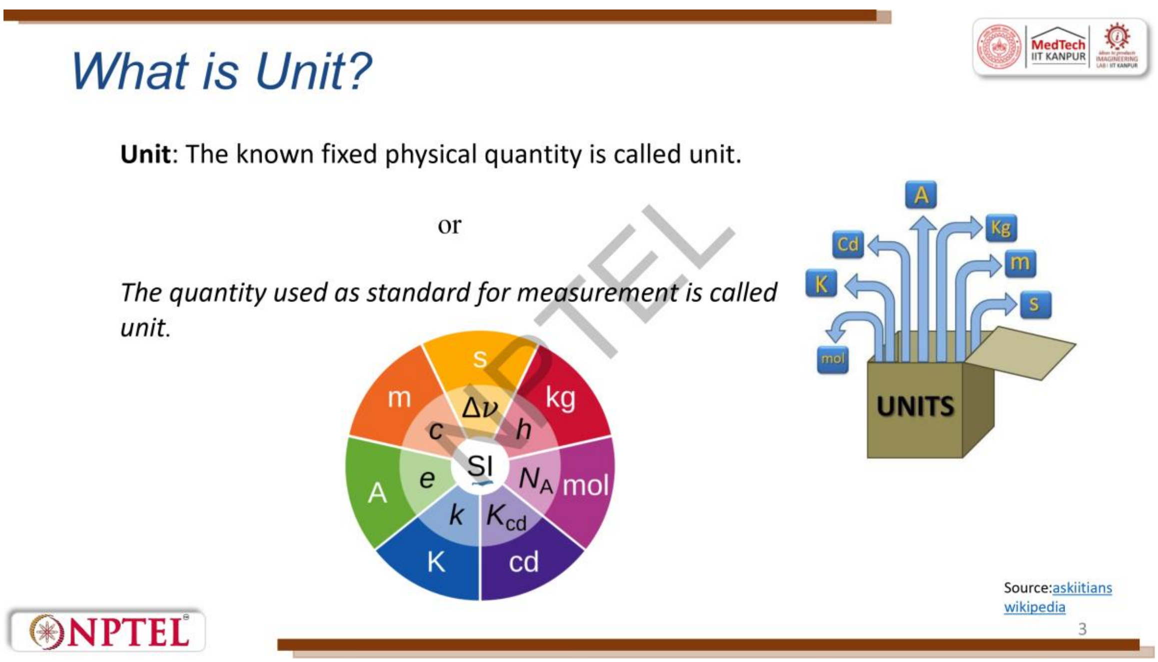


The content of this lecture is going to be, first let us understand Units, its characteristics and classification.

Next, we will try to do various systems of units because when you travel across countries or when you look at different specifications maybe sometimes for car, rocket or for a house, right, they talk in different units. But your mind has to convert it into one single unit such that you can have a feel for it. So, a small exposure to multiple systems of unit will be there. Next, we will try to cover dimension and dimensional formulas. Classification and units of physical quantities will be next.

Then we will try to solve or understand problems on dimensions. Then Dimensional Analysis and its application. Limitations of dimensional equations. We will have a recap of the lecture. After every lecture, we will try to have a recap.

Then finally, we will have references. And, I will also try to give you one or two simple problems which are only for your understanding based upon the lecture what we discussed.

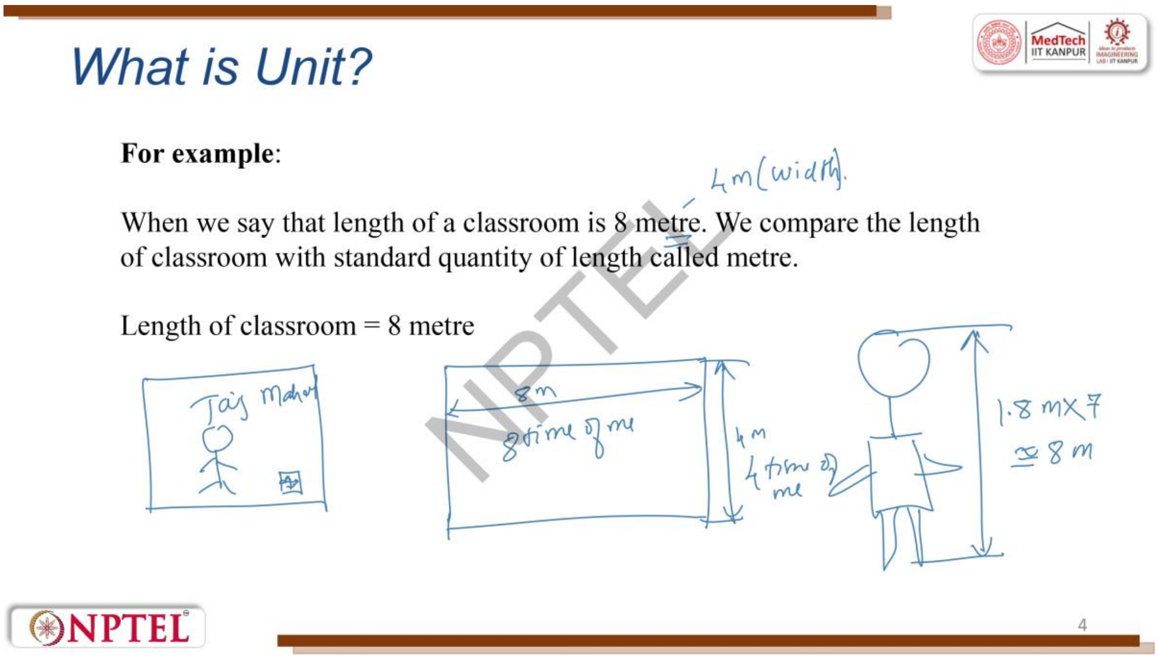


What is unit? It is a very fundamental question. The known fixed physical quantity is Is called Unit.

There can be several units like this. In Chemistry, you see mole. In Material Science or again in Chemistry, you see Kelvin. Then you see Cd. Ampere in Electrical engineering.

Kg in mechanical or in aerospace. Meter and second. These are all units. The known fixed physical quantity is called unit. The definition can also be looked like this.

The quantity used as standard for measurement is called unit. There can be this way or that way. If you see this, I have taken SI units and then I have written two circles. We will see this more in detail later. So these are all different units.



Let's try to see an example. When we say that the length of a classroom we sit in is 8 meters, we don't have a field for 8 meters. But what do we have a field is a centimeter, a millimeter and then to a large extent, a meter. If I ask you to find out your height, so you will sometimes say that okay, I am 1.8 meters. Now you know you are 1.8 m, so if you still want to have a field for 8 meters, so what do you have to do is, you have to multiply your height into maybe 7 times approximately to get a number which is close to 8 meters.

So, now you have 8 meters field. So, why did we do this exercise? To have a field for a length. And, if I say, the classroom width is 4 meters, this is the width. So, then what you do is, you try to draw the classroom and then you try to say this is 8 meters and this is 4 meters.

I still don't have a field. So, what do I do is, I try to understand eight times of me and four times of me. So, now I try to have an understanding of the length of the classroom. And, why did we use this eight meters? Because eight meters is standard.

You are converting your height into a standard so that you can have a field. So, in order to express this, you need to have a unit. Magnitudes have no meaning without units. For example, you would have taken a photo of yourself in front of Taj Mahal. So, you will have a photo and you will be standing there.

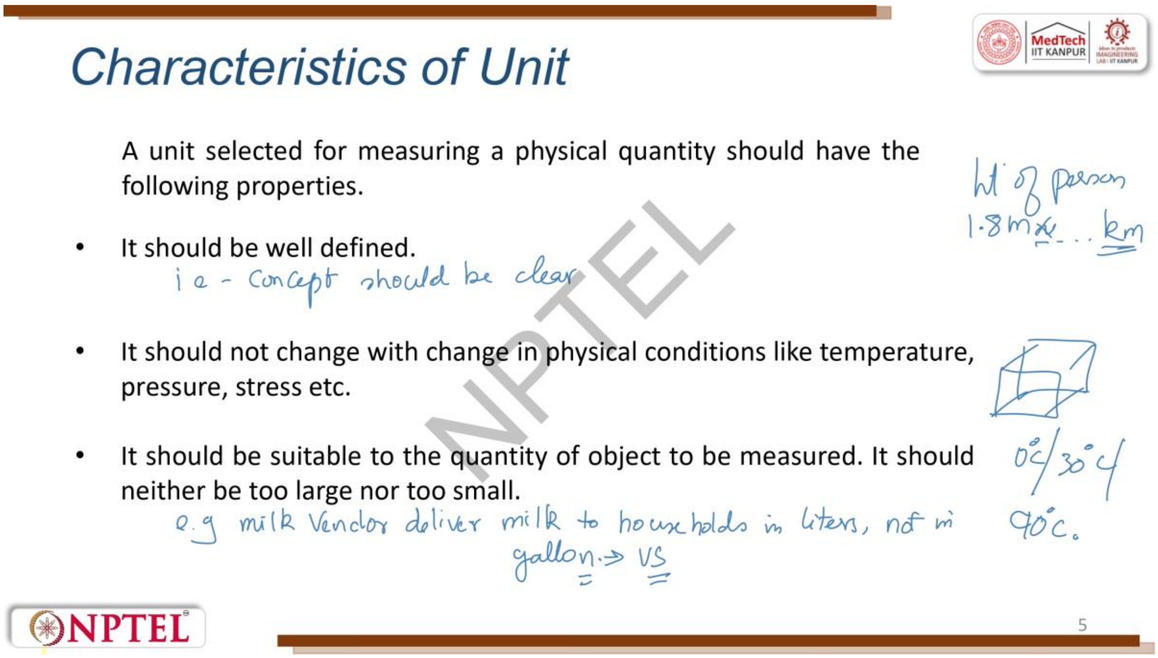
You'll be standing somewhere and you will be trying to have a feel. Now, if I want to understand what is the height of Taj Mahal? So, then what do you do is, you multiply, you know, your height from the photo. You try to figure out what is the height, you will not be able to do. I know one pixel in the screen.

What is the width and length of it? I converted into meters from here, I can try to find out what is the length of Taj Mahal. So why did we do all these exercise? We did this exercise because we have something in front of us and when we have something in front of us, we have to find out the dimensions. If we find the dimensions and units, then we can try to have a feel what should we do next.

You can visit to a nearby church. You can visit to a nearby temple or a mosque. Stand in front of the mosque or temple or your school or your college and try to have a feel with your unit dimension, whatever you know. So this exercise is clearly to tell you what is the importance of units. Right. When we say that the length of the classroom is eight meters, we compare the length of the classroom with a standard.

Quantity of length is called meter. You might have a scale, you might have yourself, or you might have a chair, a known height of a chair, and then you do it. Sometimes when you look at recipes, which is told for cooking, so they say, try to take 200 ml of water. So, now the biggest challenge is you don't have a beaker at your home. So, what generally we do is we try to make an approximation.

We try to say, okay, this glass tumbler, whatever is there, is worth of 200 ml holding capacity. Then we try to make that as a standard. Now, you look at it, you try to make the reference on a non-standard cup for which there is no graduation. So, if you look at all these things, units importance is felt.



When we try to look at characteristics of unit, a unit selected for measuring a physical quantity should have the following properties.

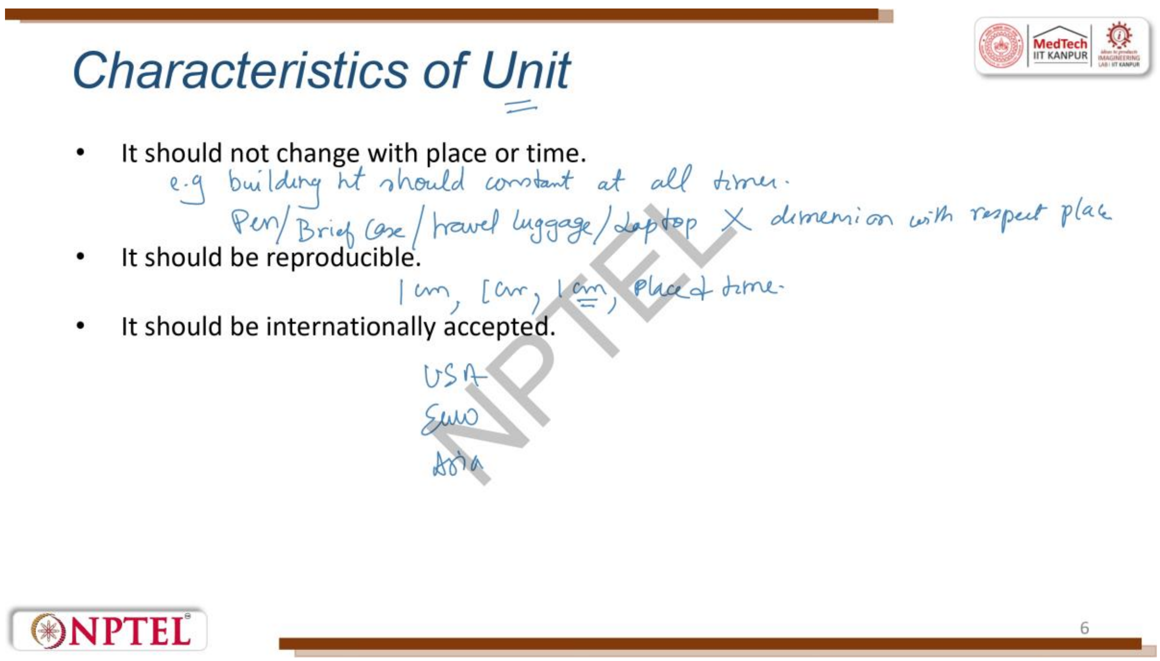
The first one is it should be well defined. That means, to say the concept should be clear. So, it should be well defined, right. So, it should not change with change in physical conditions like temperature, pressure, stress, etc. For example, you try to take an ice cube.

You measure its dimension. Now when you measure its dimension at 0 degrees, it will be different. At 30 degrees Celsius, it will be different. If you do it at 90 degree Celsius, it will be different. So, when you try to take a dimension and when you try to keep talking, we always have to be very clear that the unit should not change in physical conditions like temperature, pressure, stress, etc.

Or when we are trying to solve some thermodynamic problem where in which, we clearly state thermodynamic problem is, where temperature is involved and it is dynamically changing. So, we clearly state that in this problem, temperature is at this temperature, at this pressure, this is what is the measured quantity. They make it very clear, right. But keep in mind that it should not change with change in physical conditions like temperature, pressure, stress, etc. It should be suitable to the quantity of object to be measured. It should neither be too large or it should not be too small.

So we can take an example of a milk vendor. A milk vendor is who delivers milk to households in litres. In India, at least we do it in litres and not in gallons which is generally used in US. When you go to a mall or a marketplace, there they sell milk at gallons. So, what I am trying to say, it should be suitable to the quantity of the object to be measured. It should neither be too large or it should not be too small. The other example is, I cannot say a height of a person who is 1.8 meters tall.

I cannot say him as something which is related to kilometer. Okay. I cannot say him. Okay. He 1.8 meters is one thousandth of a kilometer. I cannot say he is one thousandth of a kilometer, which is the height.



So, when we look into the characteristics of the unit, it should not change with place or time. For example, the building height should be constant at all times.

The other thing is the pen, what you carry or the briefcase or the travel luggage or your laptop should not change the dimensions with respect to place. That's what we are seeing. So, it should not change with place or time. It should be reproducible. Today, I measure it with a scale. If it says 1 centimetre, tomorrow when I measure, it should also say 1 centimetre. And, day after tomorrow I measure, it should again say it is 1 centimeter. So, the centimeter scale is reproducible and the object also make sure the object does not expand or contract.

If it expands or contract, that is a different study. So, it should be reproducible. The unit should be reproducible and it should be again with respect to place and time, it should be reproducible. Then it should be internationally accepted. That is the characteristics of a unit. For example, inches, feet, though it has been used, when you look at a building, we talk about square feet, right. So, when we try to buy a shaft, we try to say 6 inches.

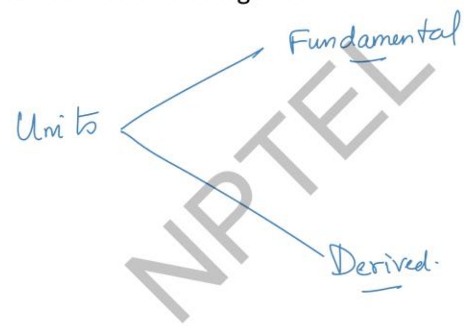
When we try to measure the dimensions of a window or a door, we tell in terms of inches, okay. So, internationally, inches are accepted. But in SI units, we have another equivalent comparison. We always know that comparison. We try to map it with it, multiply it. So, when somebody comes and says, my house is so many square meters. So, then the architect or the common mason multiplies it with a factor of 10 or 11, whatever it is, and he converts it and then he has a feel for it.

So, whatever scale you use, it has to be internationally accepted. So when we go back and look into the characteristics, it should be well defined. It should not change with change in physical condition like temperature, pressure. It should be suitable to the quantity of the object to be measured. It should not change with place or time. It should be reproducible and it should be internationally accepted.

So, that means to say, you go to USA or you go to Europe or you come to Asia, anywhere you go, the standard has to be accepted. That's why, today we have publications of papers which are coming. In that they have units which are standard with everybody has a feel for it.

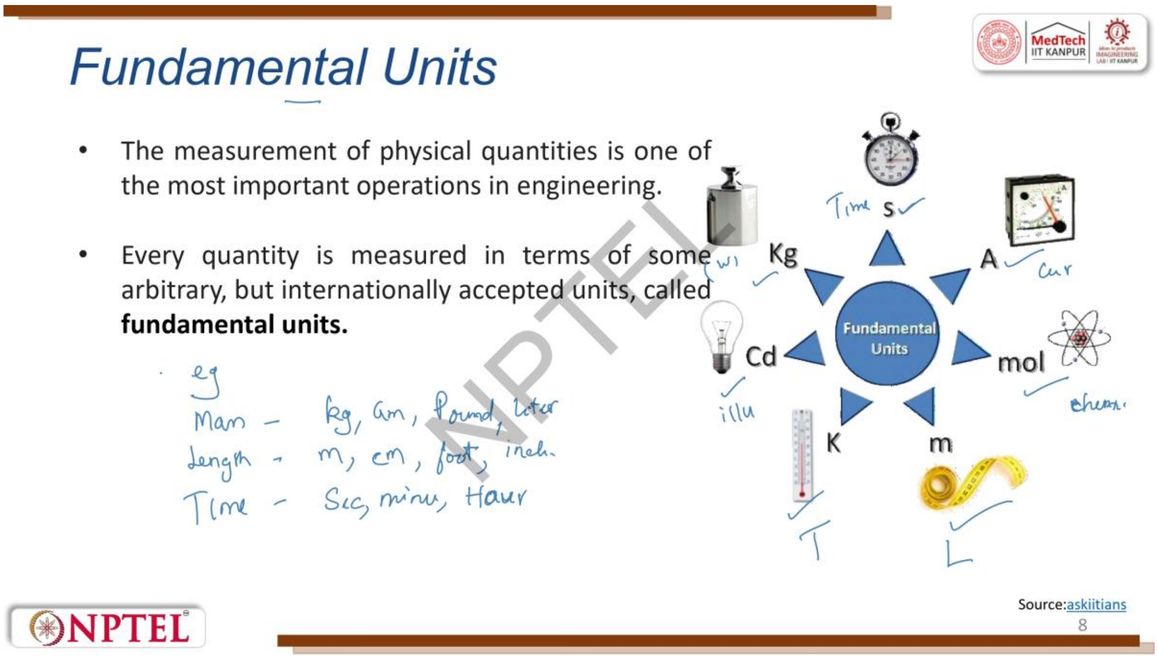
Classification of Units?

Units can be classified into two categories:



Now let us look into classification of unit. The units are basically classified into two categories. So they are units. One is called as Fundamental and the other one is called as Derived.

One is called as fundamental units and the other one is called as derived units. Why do we have Derived units? Maybe some objects or some situations are there where in which you can't use the fundamental one, but you try to extract from fundamental and have a new unit where in which it is called as derived unit. From here, you will be able to go back to the fundamental unit.

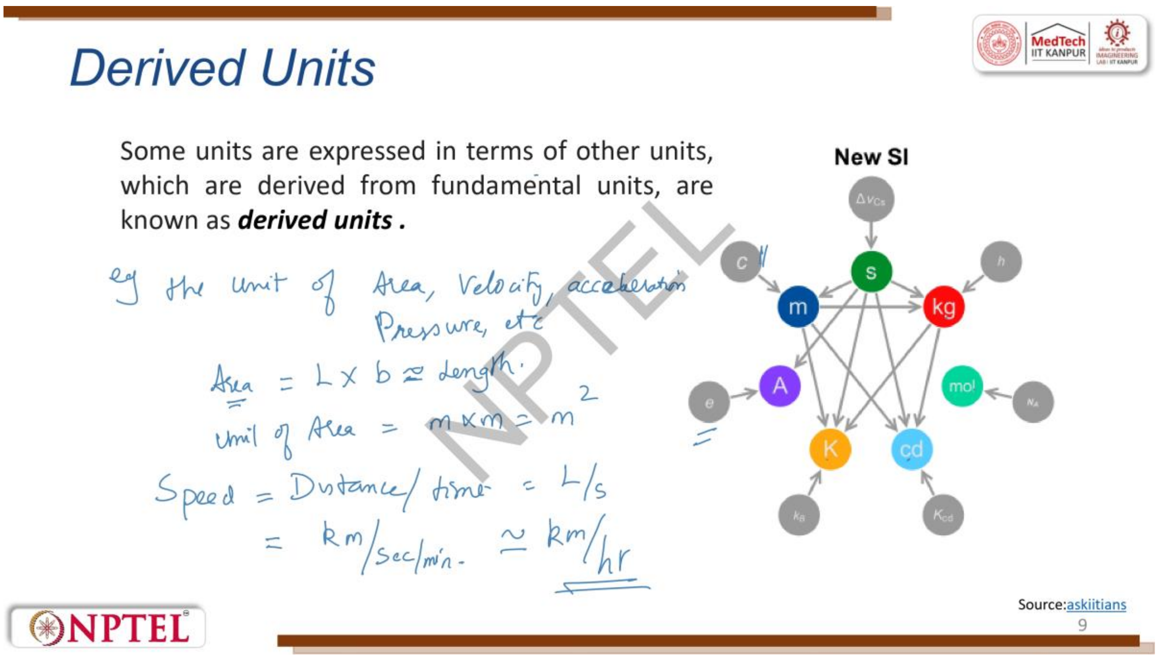


So, what are fundamental units will be the next question. The measurement of physical quantities is one of the most important operations in engineering. If you don't know to measure, then no point in producing it. Suppose, if I don't know to evaluate, let it be a person, if I don't know to evaluate a person with respect to height, weight, then it is very difficult for reproducing the same. So in engineering, Units are very, very important. The measurement of physical quantities is one of the most important operations in engineering.

Every quantity is measured in terms of some arbitrary but internationally accepted unit called Fundamental units. So, these are the seven fundamental units. You can see amperage for current measurement, mole which you use in chemistry, meter to measure the length, Kelvin to measure the temperature, the illumination, we measure it with Cd. Weight in terms of kg and S is in seconds, which is respect to time. So, you will have length scale, you have temperature scale, you will have time scale, you will have weight scale, then you will have illumination, then current, then mole.

This is used in atom or chemistry, I will put it like this, mole. So, these are the seven fundamental units. So, example, mass, you can use kg, gram, you can use pound, liter. Even today when you fill air, they talk in terms of pounds. The next one is when you talk about length scale, you can try to have meter, you can try to have centimeter.

You can try to have foot. You can try to have inch. The next one is time scale. You can try to have in seconds. You can try to have in minutes. You can try to have it in hours. So, these are some of the quantities which are used internationally, but you will have to convert all these things into some fundamental things so that you can always measure it and evaluate it. Every quantity is measured in terms of some arbitrary, but internationally accepted units are called as fundamental. So, mass can be measured in any of those things. Pounds are used in US, they use in pounds. Pressure, what you fill to your tyre, they talk sometimes in pounds. So liters, yes, we use it in for milk measurement and other things.



So what are Derived units? Derived means you extract from something. So, the derived units are extracted from fundamentals. Some units are expressed in terms of other units, which are derived from fundamental units are called as Derived units. So, you have the 7 basic things, 1, 2, 3, 4, 5, 6, 7.

These 7 are the fundamental things and whatever you try to extract from this, we call it as derived units, okay. So, from ampere, you can try to talk about electron, right. And then you try to talk about meter, you try to talk about centimeter, right. So, these are some of the derived units. So, the derived unit example, the unit of area, velocity, acceleration. Okay, pressure are all derived.

For example, Area = Length x Breadth, which is taken from a length scale.

Okay, so units of area will be meter x meter. So, that is always expressed as meter square (m^2). So, this is a derived unit. So, let us take one more speed. Speed = Distance/Time, you can express this distance in kilometers, meters, with respect to second or minute or whatever it is, right. So, this is distance is in length scale and time is in second scale, right. So, here the units can be approximately that the speed can be kilometer per hour.

So, that is what is a speed which we talk about when we go in a car or in a rocket or something. So, speed is a derived unit. Area is a derived unit. Now I am sure you will be clear with what is fundamental and what is derived. And why are derived units required? In order to have a better understanding of the specimen or the space or the situation, we always go for derived units.

Derived Units

Some commonly used *derived units.*

S.No.	Quantity	Symbol	Units
1.	Linear velocity	V	m/s
2.	Linear acceleration	a	m/s^2
3.	Angular velocity	ω	rad/s
4.	Angular acceleration	α	rad/s^2
5.	Mass density	ρ	kg/m^3
6.	Force, Weight	F, W	N ; 1N = $1 kg\text{-}m/s^2$
7.	Pressure	P	N/m^2
8.	Work, Energy, Enthalpy	W, E, H	J ; 1J = 1N-m
9.	Power	P	W ; 1W = 1J/s
10.	Absolute or dynamic viscosity	μ	$N\text{-}s/m^2$
11.	Kinematic viscosity	v	m^2/s
12.	Frequency	f	Hz ; 1Hz = 1cycle/s
13.	Gas constant	R	J/kg K
14.	Thermal conductance	h	W/m^2 K
15.	Thermal conductivity	k	W/m K
16.	Specific heat	c	J/kg K
17.	Molar mass or Molecular mass	M	kg/mol

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So, some of the fundamental derived units, or let me not confuse you, I have put some of the derived units.

So, you can have linear velocity, linear acceleration. Linear means along a line. So the symbol can be V. The units can be m/s. The acceleration will always be expressed in terms of m/s^2. So it will be two times in second. So, second square. So, this is linear. This is angular. θ is there. So, this is angular. This is linear.

OK, so angular means, it is measured in terms of θ, which is rad/s. The acceleration can be rad/s^2. So, you should also understand these are all the standards, Ω and α. And α are the standards. So, the next one is density. Why is density very important? You can see sometimes, a truck will be fully loaded with a paddy straw, you can see.

And if you measure the weight, it will be very less. But if you look at the volume what it occupies, it is too large. Vice versa, you try to take a lead bar. It will be too small, but the weight is very high. The volume is too small. So now, if you try to do comparison, then immediately what comes into effect is density.

When we have different types of oil, we try to also measure the density. The water, oil, density we measure. Water, kerosene, petrol, density we measure. So Density = Mass/Volume kg/m^3. Then when we want to measure force or weight, we always try to write force is F and weight is W. So force will be expressed in terms of Newton and 1 Newton can be expressed in terms of kg-m/s^2. Then pressure or stress to a large extent have the same units.

P is expressed for pressure and stress will be expressed in terms of sigma, which will beN/m^2. It is nothing but force per unit area, right. Then work, energy, enthalpy will be again represented as W, E and H. So you should be very careful. Sometimes we express work in terms of W, weight in terms of W. But in some of the problem statements, it will be clearly specified as the weight is W. Okay, and the work is done will be some other unit.

So, please watch out for the units. So, the work can be expressed in joules, energy also in joules, enthalpy also in joules. Enthalpy joules, you see I can express joules in Newton meter. So, now if you look at it, Newton comes from the force and meter comes from the length scale. So, this is a derived unit. In engineering, we use all those things.

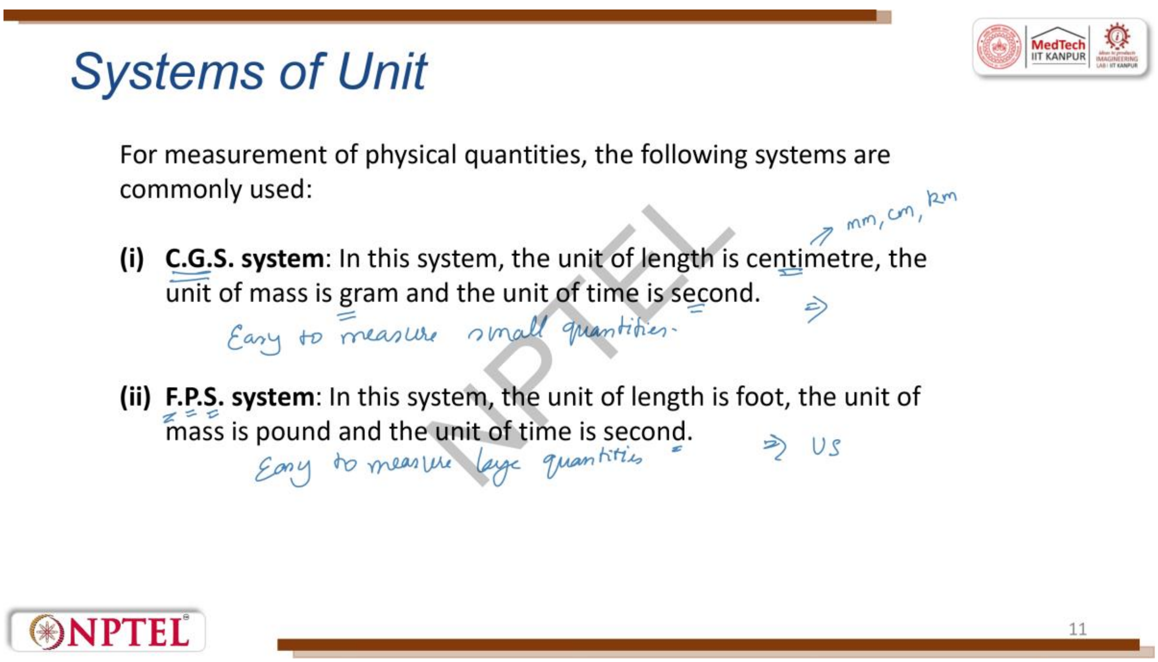
Power is expressed in terms of P. So, P can be in watts and 1 watt again you can see, it is linked to J/s. So, what you measure unit consumption of your house, energy meter will always be energy, which will be J/s. So, E/s is watts. So, absolute or dynamic viscosity. Viscosity is very important. When you are traveling by flight, the air viscosity. When we are trying to drop a ball inside oil, it's again viscosity.

When the ketchup sauce, tomato sauce comes out of the bottle, it is viscosity. So, you have absolute viscosity, you have dynamic viscosity, which is expressed as mu, which is nothing but Ns/m^2. Then you have kinematic viscosity, you have dynamic viscosity.

Kinematic viscosity is expressed as m^2/s. Frequency is a time related thing, which is expressed in F, which will always be talked in terms of hertz.

What is frequency? Frequency is 1/time, right. Then gas constant in the pressure thermodynamics problem, we always use gas constant. Gas constant is expressed as R, which is J/kg mass. Then thermal conductivity is expressed as K, which is W/m K. Thermal conductance is expressed as H, which is W/m^2 K.

Please watch out the difference. This is stocked in terms of meter square and this is stocked in terms of meter length scale and this is you have a meter square, it is area is also there. So, then specific heat C which is J/kg K then molar mass or molecular mass is M which is kg/mol. So, when looking into all the derived units, now you have a better feel, why do we need to have fundamental units and and derived units? Now, we have understood the importance of fundamental units and derived units.



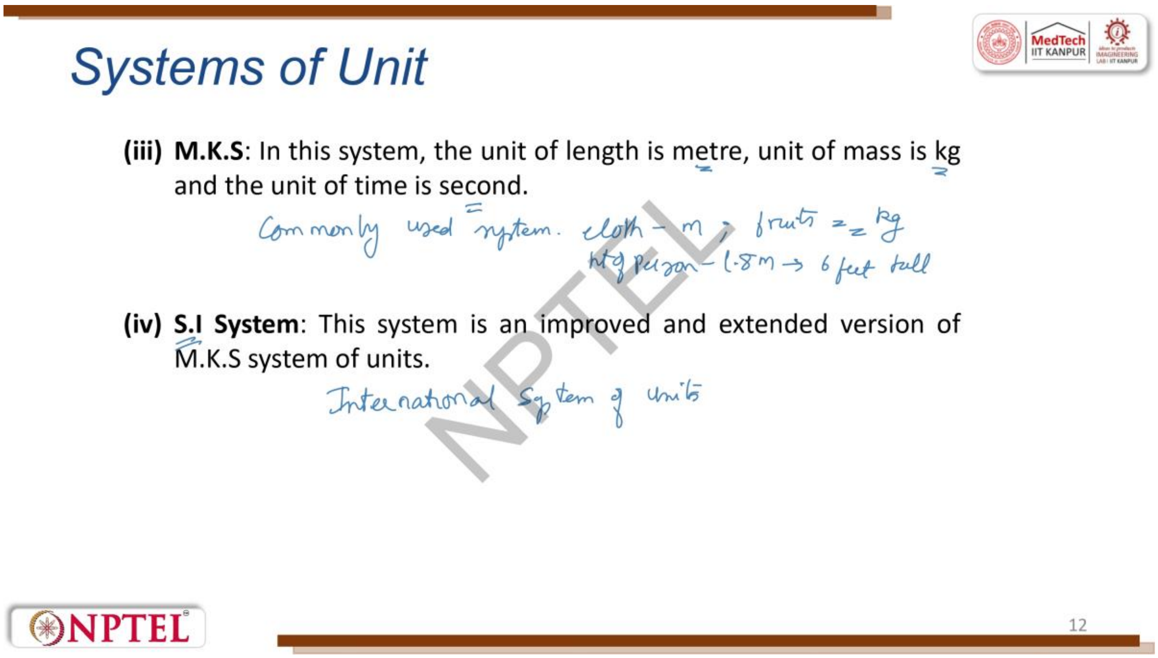
Now, let us see what are all the different systems of units for measurement of physical quantities, there are several systems. We have been using CGS system, we have been using FPS system, SI system and MKS system. Even now, it is on and off used. People have become smart enough to understand, to convert scales and then try to pick up the units. And, if you have online, when you write a program in MATLAB or in any other software, we just define the units as is in CGS and MKS and things.

It tries to convert it. Or if you go to Google today, you have a lot of conversion system calculators available. So, it is not so important to memorize, but you should understand the importance of it. So, CGS system, here the unit of length are talked in terms of centimeter. And, the mass is talked in terms of gram and the time is talked in terms of second. You should understand centimeter is when you have a length scale in millimeter or in centimeter.

Suppose, if you have it in kilometer, so then it becomes very difficult to use this scale of centimeter. And, sometimes what is happening when you go smaller? For example, if I want to measure the dimension of an ant. So then it is very difficult, the width, the diameter, it is very difficult. If I want to measure the length and diameter of your hair, very difficult.

So, CGS had this problem. So, CGS is always convenient, easy to measure small quantities. When we go for FPS in this system, the unit of length is used. Here it was centimeter. Here it is foot. And then we use pound. Then we use unit of time is seconds. So, here it is easy to measure large quantities. Of course, seconds are always small, but pound and if you say foot compared to centimeter, CGS system, it is easier.

So, FPS is used again in US, they use it. And, CGS system is slowly, it is getting obsolete, but still the old books, wherever you go through fundamental good books, they have used CGS system for solving problems and discussion and other things.



When we look at MKS system, the MKS system, the unit of length is meters and then you will have mass in kg and unit of time in seconds. All the three had the time units as the same seconds. It is very commonly used system. This is MKS is commonly used. So when we buy clothes, we always try to measure in meters, height of a person.

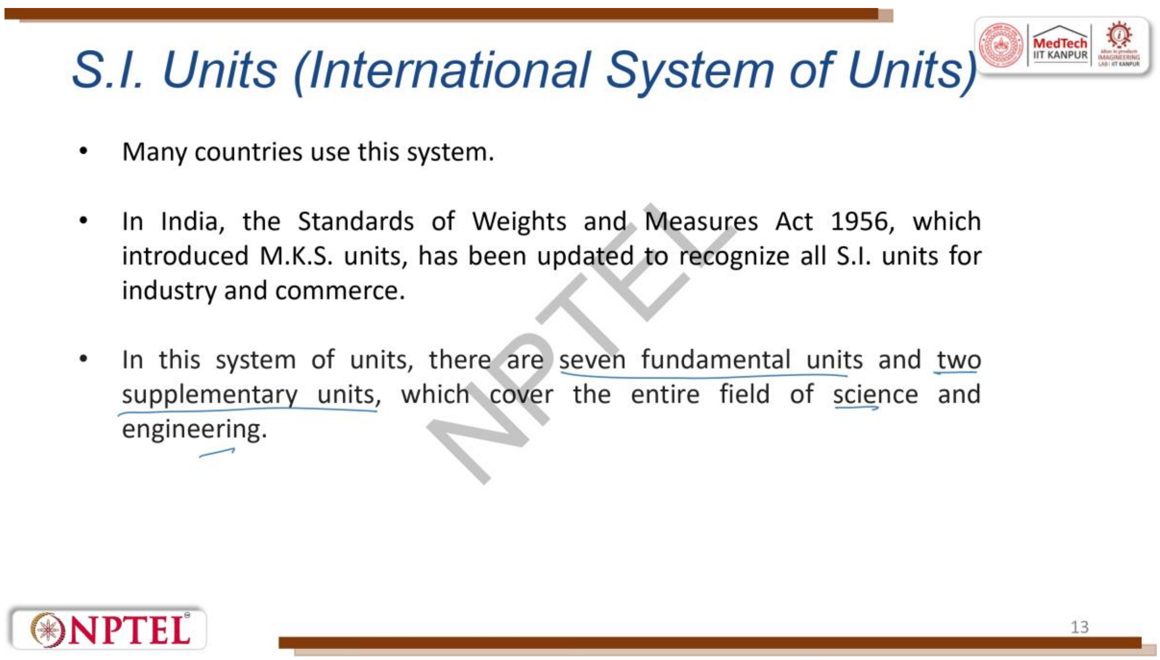
We always talk in 1.8. We interestingly talk in feet. Okay. But we also talk in meters, right. Height of a person in meters. But generally what we do is we talk, we say that you are six feet tall. Right. So, we do that. And when we buy fruits, we buy it in kg. It is commonly used. Okay. The improvised system of MKS is SI. So, here the system is an improved and an extended version of MKS system of units is SI. So, we call SI as international standard.

Standard or international system of units. If in colloquial term, we call it as international standards. So, what is now expected is the world is moving towards using of SI systems. And why did we go through all these things, the 4 units? Because some problems can be defined or some measurements can be defined in CGS, FPS or MKS.

But you have to understand what is the units, convert it into one standard unit and then start solving the problem. That is what it is. So, it is only playing with the unit scale conversion. And why are these units very important? In the derived units, you saw so many units are there, right. So, now we should understand which unit comes where and what should be the conversion scale such that I bring everything to SI system and then start solving the problem. So, when you try to solve it, whatever answer you get will be a standard one. In fact, it is a good idea to change all the units what is given in the problem to a standard and then start solving.

That should be the step 1. Write down all the units given in the problem. That will be step 1. Step 2 is try to convert all the units whatever is there into a single standard unit. And then you try to solve so that you will not have any magnitude error. And the other thing is, as engineers you should also start having feel for what is the answer which comes.

For example, the diameter of a shaft required to operate a rotor or a motor. A motor cannot be 1 centimeter, cannot be 5 mm. So, if you have the units and when you try to conclude the problem, you have to look at the magnitude and the unit for the problem which is defined. You can see if there is an error, you can go back and correct the error very fast.



So, SI units is the International System of units which is used in many countries, right. In India, the Standards of Weight and Measurements Act 1956, which introduced MKS units, has been updated to recognize all SI units for industry and commerce. In this system of units, there are seven fundamental units and two supplementary units, which cover the entire field of science and engineering. So, this is very very important. There are 7 fundamental units and 2 supplementary units which covers the entire field of science and technology. Now in India, the standard what we are following is SI units. And internationally also, we are moving towards that. The next one is dimensions. So till now, we were looking at various units.

S.I. Units (International System of Units)

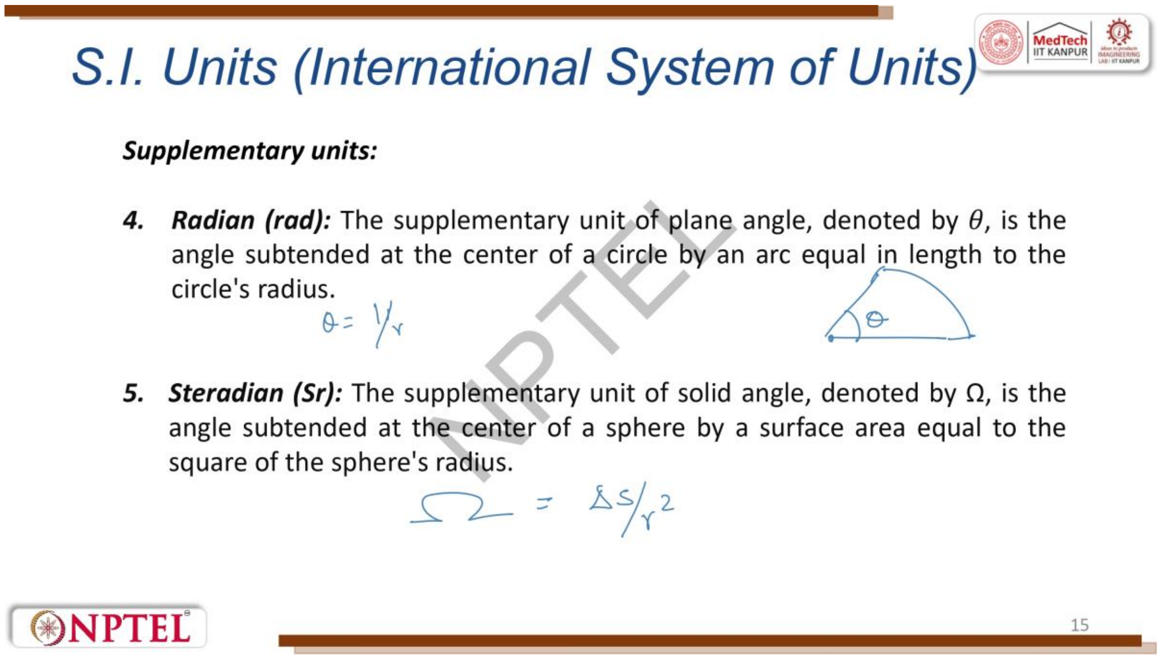
Definition of Basic Units of S.I.

1. **Metre** (m): Metre is the length of the path travelled by light in vacuum during a time interval of 1/299792458 of a second.
2. **Kilogram** (Kg): Kilogram is defined as the mass of international prototype (standard block of platinum-iridium alloy) of the kilogram, kept at the International Bureau of Weights and Measures at Sevres near Paris.
3. **Second** (s): The second is the duration of 9192631770 periods of the radiation corresponding to the transition between two hyperfine levels of the ground state of Cesium- 133 atom.

First we looked at, so what are the basic SI units? First is length what we measure. It is expressed in meters. Meter is the length of the path travelled by light in vacuum during a time interval of 1 by 299792458 of a second is the standard which they have used for meter.

So that means to say the measurement meter is expressed is the length of the path traveled by a light in vacuum. So this is a standard, right. Next is kg (kilogram). kg is defined as the mass of international prototype standard block of platinum iridium alloy of the kg kept at the International Bureau of Weights and Measures at Severus near Paris. So, this is the definition for kg.

Second is the duration of 9192631770 periods of the radiation corresponding to the transition between two hyperfine levels of the ground state of cerium-133 atom. The transition time is defined as in seconds.



When we try to talk about supplementary units, they are radian. Radian, which is always be represent as RAD. The supplementary unit of a plane angle is denoted by θ is the angle subtending at the center of the circle by an arc in length of the circle radius.

So, you have a circle, right, This is θ. The supplementary unit of a plane angle denoted by θ is the angle subtended at the center of a circle with an arc equal in length to the circle radius. So, we try to represent this as $\theta = l/r$, where l is the length and r is the radius. So, the next one, the supplementary unit, next one is steradiums, SR. The supplementary unit of a solid angle denoted by Ω is the angle subtended at the center of the sphere by a surface area equal to the square of the sphere's radius.

So, this will be expressed as $\Omega = \Delta s/r^2$. So, these two are the supplementary units.

S.I. Units (International System of Units)

TABLE: Fundamental and supplementary units

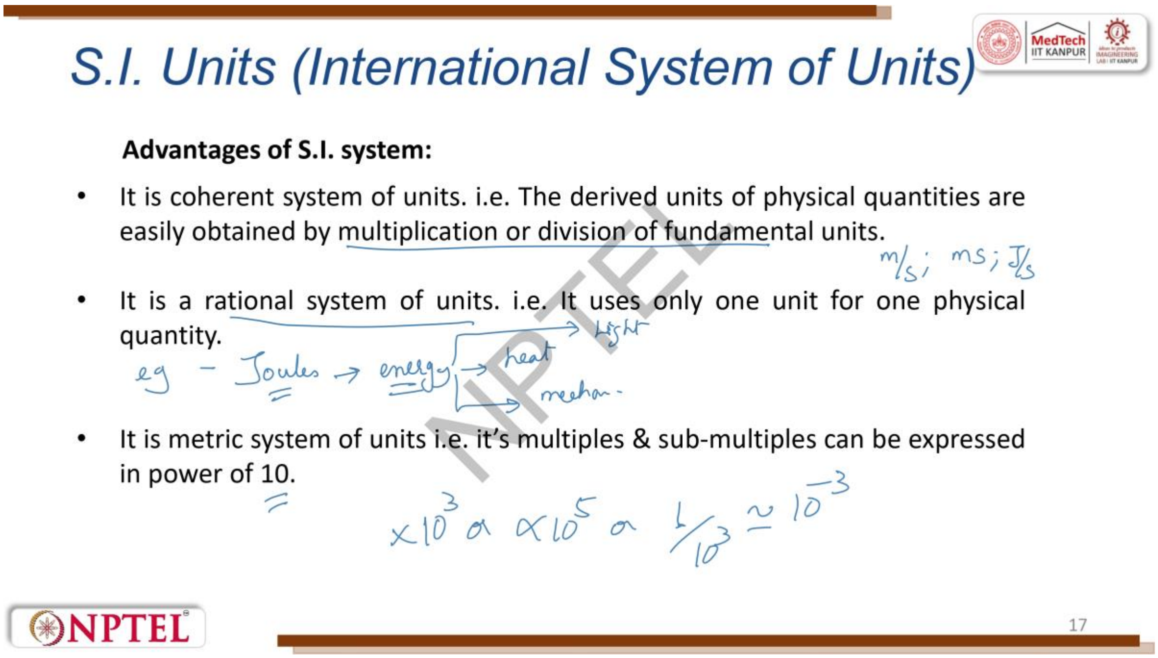
Sr. No.	Fundamental units	Unit
1.	Length (l)	Meter (m)
2.	Mass (m)	Kilogram (kg)
3.	Time (t)	Second (s)
4.	Temperature (T)	Kelvin (K)
5.	Electric current (I)	Ampere (A)
6.	Luminous intensity (Iv)	Candela (cd)
7.	Amount of substance (n)	Mole (mol)
	Supplementary units	
1.	Plane angle (α, β, θ, ϕ)	Radian (rad)
2.	Solid angle (Ω)	Steradian (Sr)

SI units

Source: https://skyhighelearn.com/how-to-do-unit-conversions-of-length-area-weight-pressure/

So, I have clearly written it. Length is L. Mass is M. Small t is time. Big T is temperature. Electric current is I. Illuminous intensity is LV. Atom of a substance is N.

So, length is expressed in meters, mass in expressed in kgs, time is expressed in seconds, temperature in Kelvin, current in ampere, illuminous intensity is candela which is Cd and amount of substance is in moles. The supplementary units are going to be plane angle and solid angle which are α and β, θ, ϕ, which is all, has a unit of radians. Solid angle is steradians, SR. So, this covers the complete set of SI units.



So, what are the advantages of SI units? SI units, it is coherent system of units, that is, the derived units of physical quantities are easily obtained by multiplication or division of the fundamental units. So, this is very important. So, it can be m/s or it can be ms. Right. It can be J/s or it can be joule whatever. So I'm just giving an example.

So it can be meter per second or meter second or joule per second. So this is multiplication or derived. It is a rational system of units.

That is, it uses only one unit for one physical quantity. Length cannot be used in meter as well as in centimeter. So that is what it is a rational system of units. The last one is it is metric system of units that is its multiplies and sub multiplies can be expressed in power of 10. So this is also important. So here if you want to see an example so we can try to see use of joules.

It can be used for energy. It uses only one unit for one physical quantity energy in all times. For example, it can be told as heat energy. It can be told as mechanical energy. It can be told as light energy.

All we'll try to use only joules as the unit. So it is a rational unit for units. So here what are we trying to say is, multiply by 3 or it will be multiplied by 5 when you try to convert it from one unit to the other or it can be $1/10^3$ which can be expressed as 10^{-3}. So, that is what we are saying here. It is metric system of units, that is, its multiplies, sub-multiplies can be expressed in terms of power, 10^3

Thank you very much.